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NAVAL POSTGRADUATE SCHOOL

Monterey, California



THESIS

CERENKOV RADIATION GENERATED BY PERIODIC
ELECTRON BUNCHES IN A FINITE AIR PATH

by

Lawrence A. Newton

December 1983

Thesis Advisor:

F. R. Buskirk

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Cerenkov Radiation Generated
by Periodic Electron Bunches
in a Finite Air Path

by

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MASTER OF SCIENCE IN PHYSICS

from the

NAVAL POSTGRADUATE SCHOOL
December 1983

ABSTRACT

Microwave Cerenkov radiation is measured for the case of bunched electron beams which exceed the velocity of light in a finite air path. The theoretical equation for prediction of the form of the power for Cerenkov radiation is tested experimentally for this case. Initial verification of the theory is observed.

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I. INTRODUCTION

Since the speed of light is modified by the index of refraction in a dielectric, it is possible for relativistic electrons to have a velocity which actually exceeds that of light in the medium. In this circumstance a phenomenon known as Cerenkov radiation arises. This radiation appears in a cone, around the direction of motion of the electrons, defined by the Cerenkov angle.

$$\theta_c = \cos^{-1} (c/nv), \quad (\text{eqn 1.1})$$

where c is the speed of light in a vacuum, n is the index of refraction, and v is the velocity of the electrons. This radiation is analogous to acoustic shock waves in air.

F. R. Buskirk and J. R. Neighbours [Ref. 1] calculated the power of Cerenkov radiation for the case where the electrons are bunched and the dielectric medium is of finite length. The experiments described in this thesis were designed to check those theoretical calculations.

Figure 1.1 depicts the pertinent physical relationships for this situation. See Table I for definitions of the variables. The first step in the theoretical derivation was to calculate the vector potential $\underline{A}$ and the scalar potential, ϕ , at a field point $\underline{r}$ resulting from an element of charge at a location within the electron bunch. A key factor in the analysis is that the current and charge densities which appear in the expressions for the potentials are periodic and may be expressed as Fourier series. Therefore, the potentials themselves may also be expressed as Fourier series, with Fourier coefficients representing the frequency components.

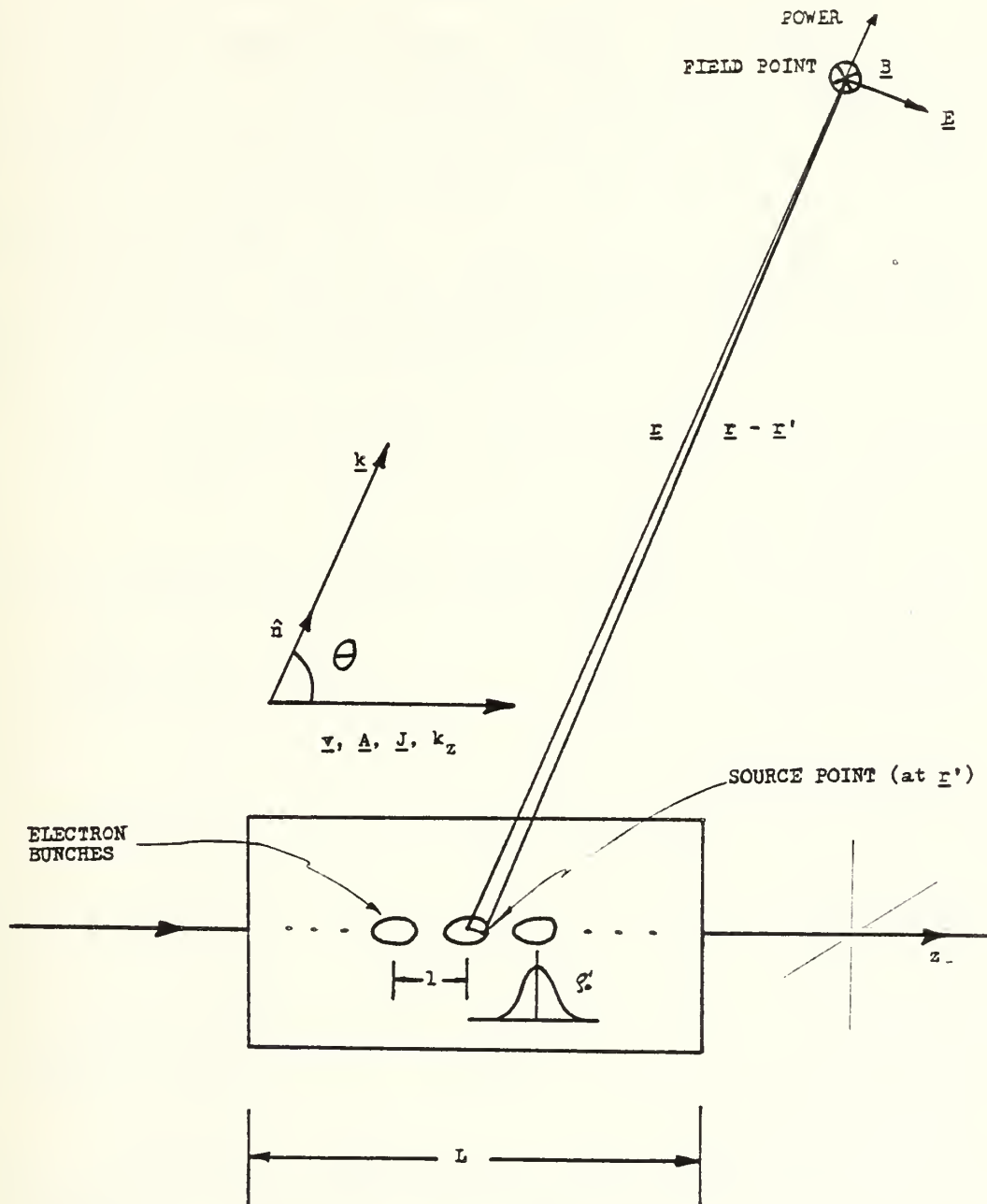


Figure 1.1 Cerenkov Radiation.

It is convenient to carry out the rest of the analysis in terms of the Fourier coefficients. The electric and magnetic field components are obtained from the potentials, and these, in turn, are used to find the frequency components of the average radiated power. An important assumption inherent in the procedure, which may directly affect experimental validity, is that the field point is assumed to be far from the source region. For details of the entire analysis, see [Ref. 2].

A principal result of [Ref. 2] is slightly recast in [Ref. 3] as the following expression for the power per unit solid angle at a given frequency,

$$W(\nu, n) = \frac{\mu}{2c} L^2 \nu^2 \nu_o^2 \sin^2 \theta |\rho_o'(\underline{k})|^2 I^2(u) , \quad (\text{eqn 1.2})$$

with the parameters defined as follows:

$$u = \frac{kL}{2} (\cos \theta_c - \cos \theta) , \quad (\text{eqn 1.3})$$

$$I(u) = \frac{\sin u}{u} , \quad (\text{eqn 1.4})$$

and

$$\rho_o'(\underline{k}) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} d^3 r e^{-i \underline{k} \cdot \underline{r}} \rho_o'(\underline{k}) . \quad (\text{eqn 1.5})$$

Refer to figure 1.1 and table I for clarification of these parameters.

The frequencies appearing in equation 1.2 are harmonics of the electron bunch frequency, which is a constant (ν_o). Thus, writing (ν) as ($j \nu_o$), and using a one-dimensional

TABLE I
Variable Definitions

$\underline{J}$	= $\rho \underline{v}$	= current density
l	= $\underline{v}/v_0$	= bunch spacing
v_0	=	bunch frequency
$\underline{v}$	=	bunch velocity
$\underline{k}$	=	power propagation direction
$\underline{n}$	=	unit vector in the $\underline{k}$ direction
L	=	length of finite emission region
$\underline{A}$	=	vector potential
$\underline{r}$	=	position vector of field point
$\underline{r}'$	=	position vector of source point
ρ'_0	=	Gaussian distribution of longitudinal bunch (charge) distribution
b	=	parameter for the charge distribution
$\underline{E}$	=	electric field vector
$\underline{B}$	=	magnetic field vector

Gaussian distribution to describe the longitudinal bunch dimension, a relatively simple Cerenkov radiation power function is given by equation 1.6 (equations 9 and 10 of [Ref. 3]). This is the expression which was used to compare theoretical to experimental results.

$$P_j(\theta) = \frac{2\mu v_0^4 q^2}{c} \frac{j^2}{4} L^2 \sin^2 \theta \left(\frac{\sin u}{u} \right)^2 \text{Exp} \left(\frac{-k_z^2 b^2}{2} \right), (\text{eqn 1.6})$$

Note that the radiation function varies with the square of the harmonic number, the length L of the emission region, and the angle at which the radiation is being observed. Note also the interference factor, similar to what might be experienced with optical radiation, and the way in which the bunch dimension, b , appears in the expression. The length of the emission region and the angle appear not only directly, but also through the factor u (see equation 1.3).

The results of this simple equation are quite interesting. Due to the finite size of the emission region, radiation no longer appears only at the Cerenkov angle, but throughout a range of angles determined by the $(\sin u)/u$ factor. Figure 1.2 shows how the radiation is spread for three different sizes of emission region. For a given harmonic, smaller emission regions cause greater spread, or diffraction of the radiation. The power is distributed to varying degrees among the different harmonics also, as depicted by figure 1.3. Higher harmonics have larger peak powers, and are peaked at a smaller angle than are lower harmonics.

For this experiment, the microwave portion of the spectrum was investigated, and the dielectric medium for the electron path was chosen to be air. The electrons were accelerated to relativistic velocities by the Naval Postgraduate School LINAC, which produces electrons with energies of approximately 100 Mev. For the theoretical calculations, a Fortran program (see appendix A) was used to calculate the power as a function of angle from equation 1.6. Variants of this program (appendices B and C) were used to superimpose data points over the theoretical curves.

The experimental apparatus and procedures are described in detail in the next chapter.

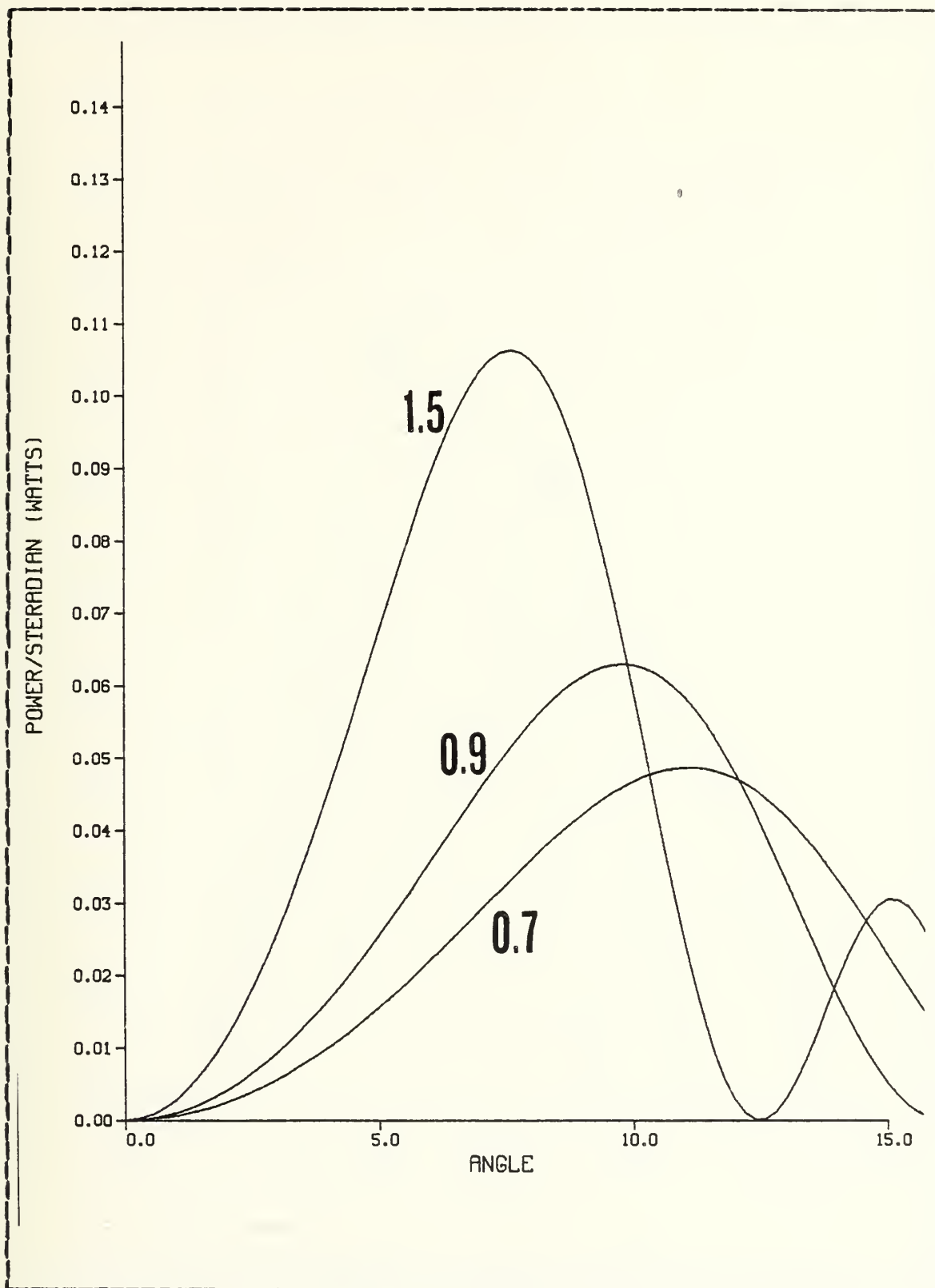


Figure 1.2 Third Harmonic for $L = 0.7, 0.9, 1.5$ meters.

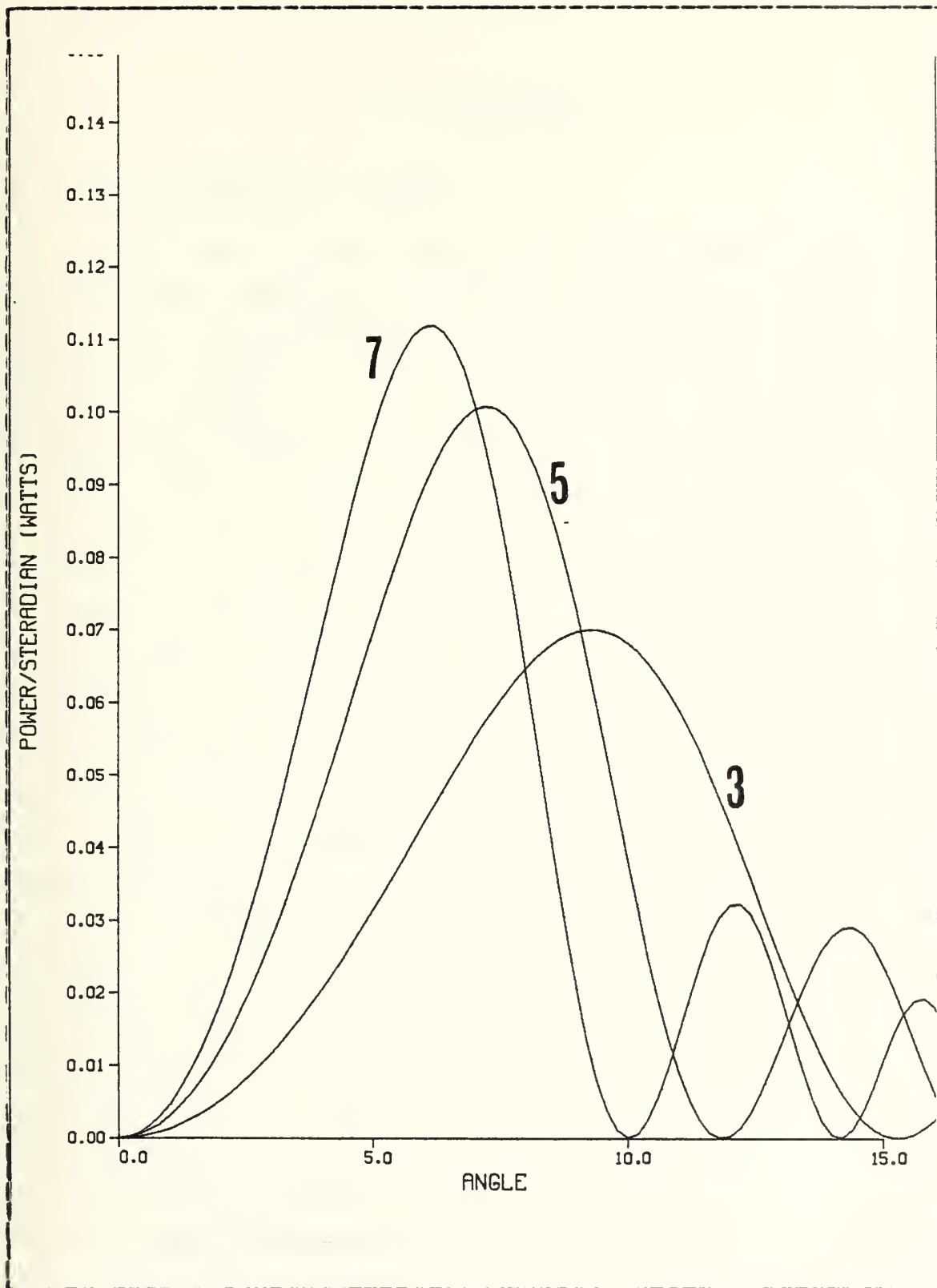


Figure 1.3 Harmonics 3,5,7 for $L = 1.0$ meters.

II. EXPERIMENT

A. BASIC EXPERIMENTAL DESIGN

The purpose of this experiment was to measure the power from Cerenkov radiation as a function of angle, in order to compare it with theoretical curves such as those depicted in figures 1.2 and 1.3. The basic design for this experiment is shown in figure 2.1. Photographs of the experimental apparatus are presented in Appendix D. The electron bunches exit the Linac aperture and emit Cerenkov radiation until they reach the aluminum mirror. This mirror allows the electrons to pass and proceed into the beam dump, while the microwave radiation of interest is reflected into the detector area. The mirror therefore performs the function, required by theory, that the radiation be emitted over a finite distance. The detector is mounted on a pivot arm, which is placed such that the detector is always pointed at the virtual center of the emission region. The pivot arm also fixes the distance from the center of the emission region to the detector, so that the distance over which the radiation travels is eliminated as a variable.

With this experimental setup, the basic experimental procedure was to sweep the detector over the angular range of interest using a small motor in the detector mount. The signal picked up by the detector was transmitted to the observer station, where it was fed into an amplifier and then into both an oscilloscope and a pulse height analyzer. The oscilloscope allowed a gross measure of power, while the frequency distribution measured by the pulse height analyzer gave a more precise value. The end result of this procedure was tabular data in the form of signal versus angle.

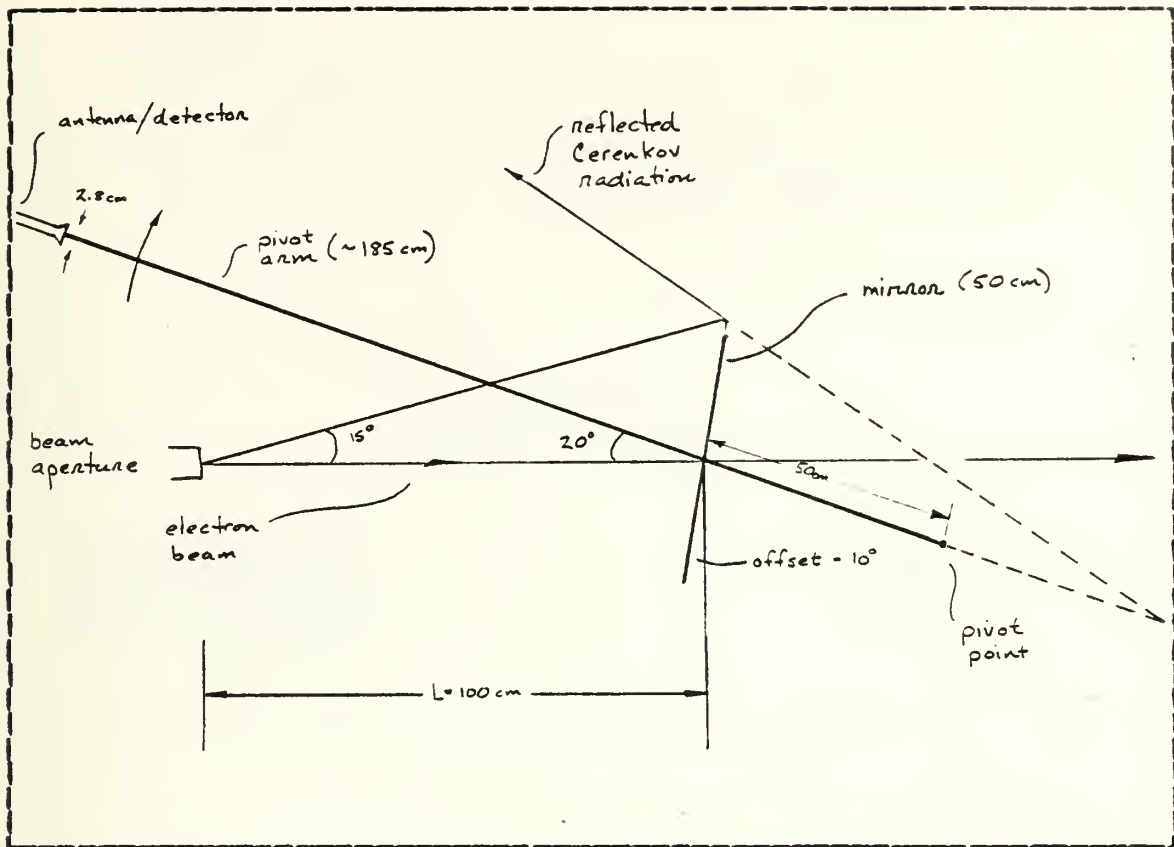


Figure 2.1 Experimental Design.

This brief overview of the experimental design is amplified in the next section with a more detailed look at various elements of the experimental apparatus.

B. EXPERIMENTAL APPARATUS

In this section, the components of the experimental apparatus will be examined, in order to provide a precise understanding of the experiment. The various components of the signal train will be reviewed in order, from the originating device itself (LINAC) to the final detection and analysis components.

1. LINAC

The salient features of the LINAC are listed in table II. These parameters are the same as those calculated by A. Saglan in prior thesis work with the LINAC at the

TABLE II
LINAC Parameters

Bunch Frequency:	2.856 GHz
Bunch Velocity:	2.997886×10^8 m/s
Bunch Size Parameter:	0.24 cm
Electron Energy:	100 Mev
Bunch Spacing:	10.5 cm

Naval Postgraduate School [Ref. 4]. These parameters also meet those chosen in [Ref. 3] which gives the theoretical curves for Cerenkov radiation. The LINAC provided fairly consistent signals for the experiments which are reported here. However, the signal eventually developed instabilities which precluded further experiments. That is, it became impossible to distinguish between signal variation due to the LINAC and that due to variation in the angle of detection. It may be that some of the experimental deviation from theory can be adequately explained by the variability of the LINAC itself.

2. Air Path

The air path was chosen to be 1.0 meter in length, which was convenient for the dimensions of the LINAC end station. The characteristic index of refraction for air was taken to be 1.000268, which is the same as that given for

air in [Ref. 3]. This gives a speed of light in air of 2.997127E08 meters per second, which is less than the velocity of 100 Mev electrons (see Table II).

3. Mirror

A polished aluminum mirror 50 centimeters in length was used to fix the path length. The mirror performed the dual function of allowing the electron bunches to pass and proceed into the beam dump, while causing the microwave Cerenkov radiation to be reflected into the detection area. The electron bunches continued to emit Cerenkov radiation after passing through the mirror. It was assumed that this radiation did not reach the detection area, due to the inherent weakness of the signal, and due to the distance and multiple reflections it would have to travel through in order to reach the detection area.

The mirror was tilted 10 degrees, causing the reflection axis to be offset 20 degrees from the beam axis. Therefore, the actual length of the emission region varied between approximately 95 and 105 centimeters. Measurements were made over a range of from 0 to 15 degrees. The mirror was long enough to reflect most, but not all, of the radiation at 15 degrees. See figure 2.1 for details of the geometry of the experiment.

4. End Station Detection Apparatus

The detection apparatus was mounted at the end of a pivot arm of fixed length. The pivot point was located at the center of the virtual image projected by the mirror, in order for the detector to always be pointed at the virtual center of the emission region. Theory assumed that the emission region would be a short distance, small compared to the detector distance r' (field point). Focusing the detector on the center of the emission region was done to

approximate theory as closely as possible. The pivot arm also kept the detector at a fixed distance from the (virtual) center of the emission region. Therefore, the distance of travel of the measured radiation was approximately the same for all angles, so that variation in distance would have minimal effect on the signal variation.

a. Antenna

A small antenna, with a lateral dimension of 2.8 centimeters, served as the forward end of the detection apparatus. This antenna served two functions. First, it was small enough that, with the given length of the pivot arm, the antenna subtended an arc length of approximately 1 degree. Therefore, an experimental measurement resolution of 1 degree was obtained. Further, this antenna had a very wide beam width. The antenna profiles for the electric and magnetic fields are given in figures 2.2 and 2.3. Using the half-power points as cutoffs, the beam width is found to be greater than 60 degrees for both the E and H fields, and thus for the power as well. At a distance equal to the average of that between the antenna and the mirror, approximately 130 centimeters, the beamwidth covers an arc length of 68 centimeters, which is larger than the length of the mirror.

Therefore, radiation arriving at the antenna and originating from any part of the emission region would be collected by the antenna. This again approximates the theoretical condition that the emission region be a point source, since the antenna "sees" the entire emission region at every angle of interest.

In summary, the antenna's narrow dimensions have provided spatial resolution, while its wide beamwidth has approximated a theoretical requirement.

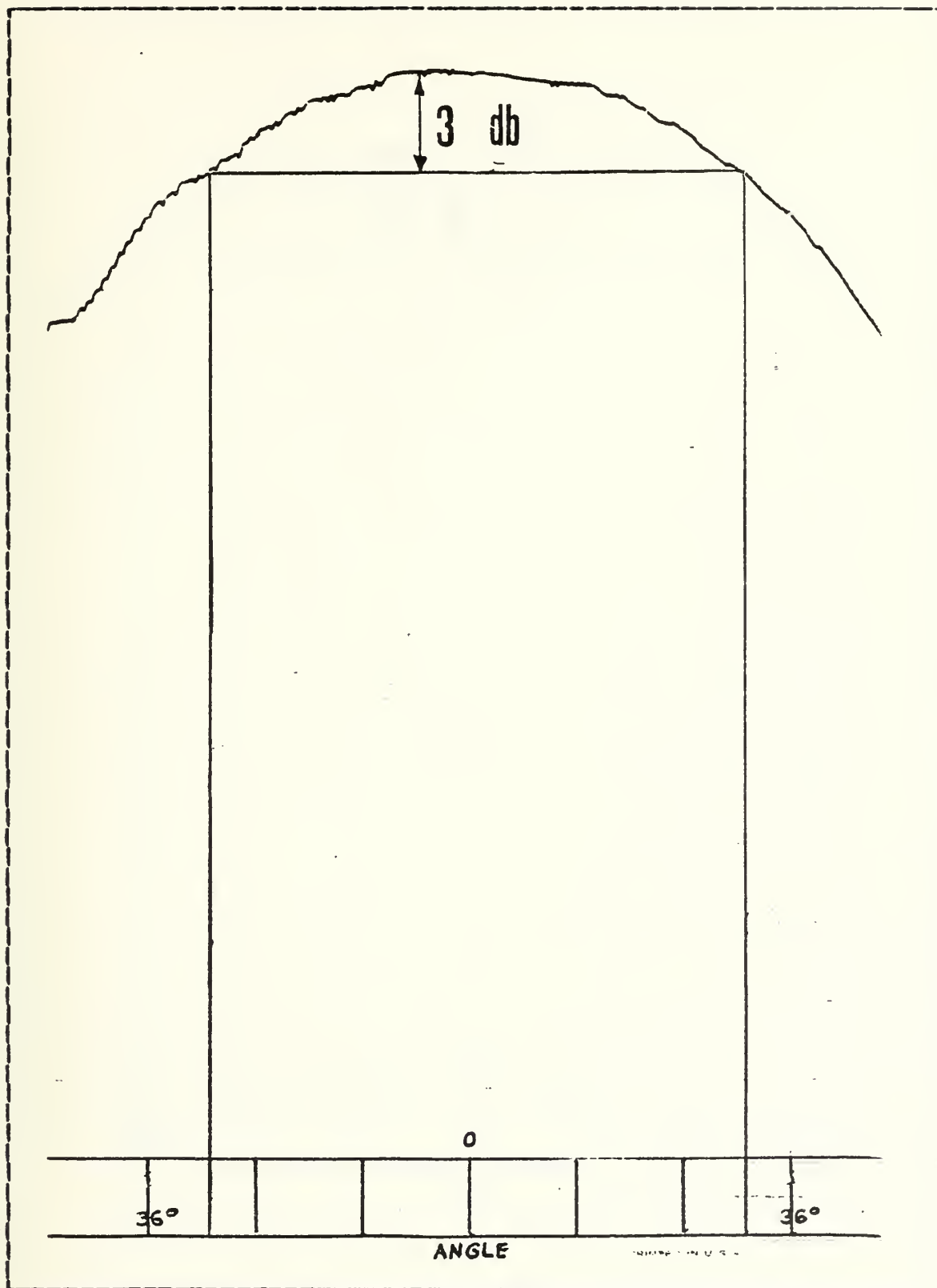


Figure 2.2 Antenna Beam Profile for the Electric Field.

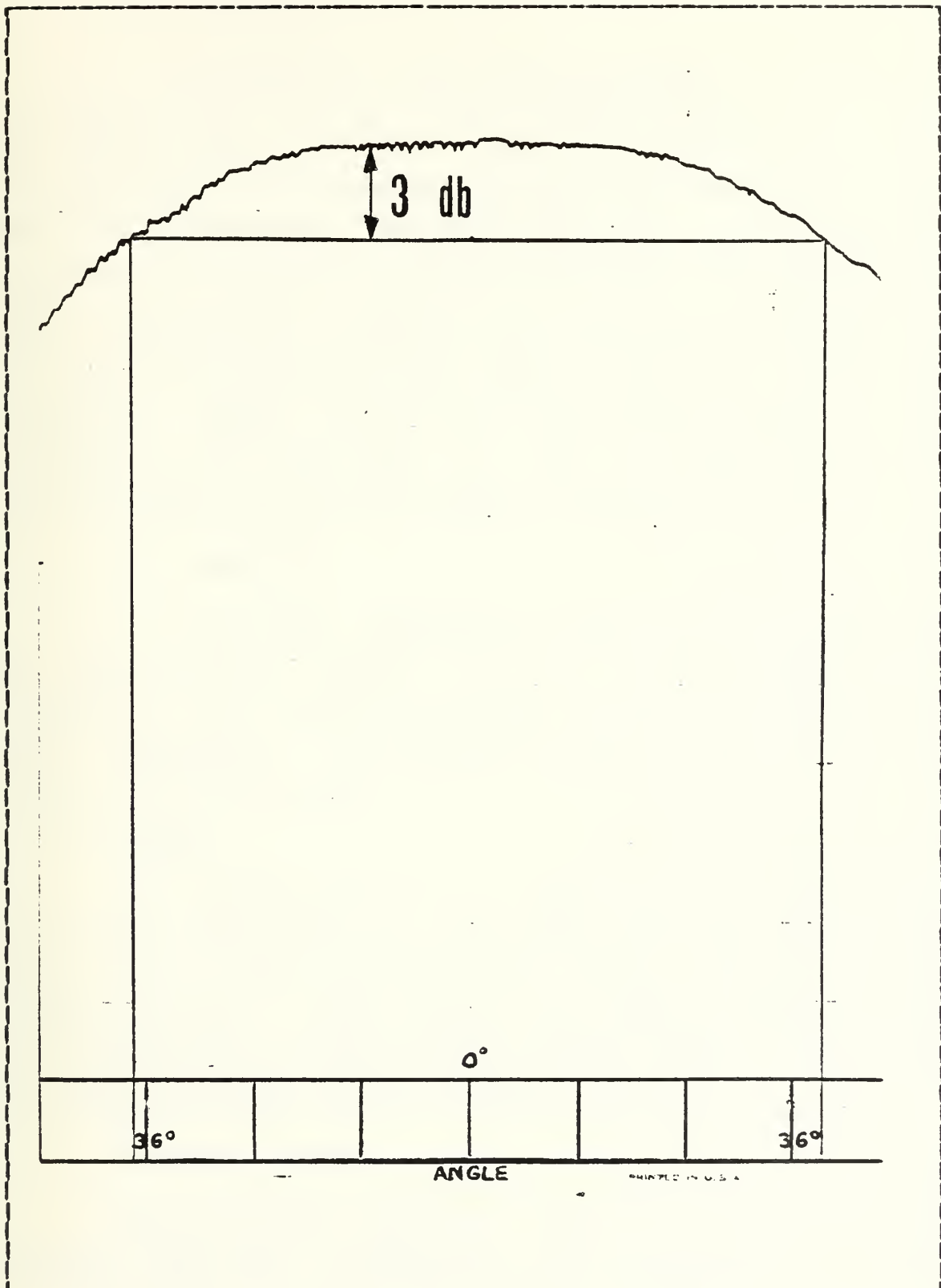


Figure 2.3 Antenna Beam Profile for the Magnetic Field.

b. Filters

In previous experiments reported in [Ref. 4] a section of X-band waveguide was included between the antenna and the crystal detector. This waveguide serves as a partial filter of the microwave radiation, since it does not pass the fundamental frequency (2.86 GHz) nor the second harmonic (5.71 GHz). Use of the X-band waveguide as a filter was included as one of the variants in this experiment. Additionally, filters were available which were able to select the third and the fourth harmonics of the bunch frequency. These filters were designed and built by K. Alexander and S. Hamel [Ref. 5]. The band-pass characteristics for these filters are shown in figures 2.4 and 2.5.

c. Detector

The final component in the detection apparatus was the detector itself, an HP X-band X424A crystal detector. The detector was used without the square-law load. Therefore, the response varied linearly with the input (Cerenkov) signal.

5. Cable

In the work done by A. Saglam [Ref. 4] the experimental area (end station of the LINAC) was described as very noisy due to the electromagnetic energy radiated by the LINAC klystrons. This problem was effectively solved in this experiment by using doubly-shielded cable to transmit the detected signal to the observer station.

6. Observer Station

The analyzing equipment consisted of an ORTEC 450 Research Amplifier, a TEKTRONIX 7904A Oscilloscope, and a TRACER NORTHERN TN-7200 Pulse Height Analyzer (PHA). The

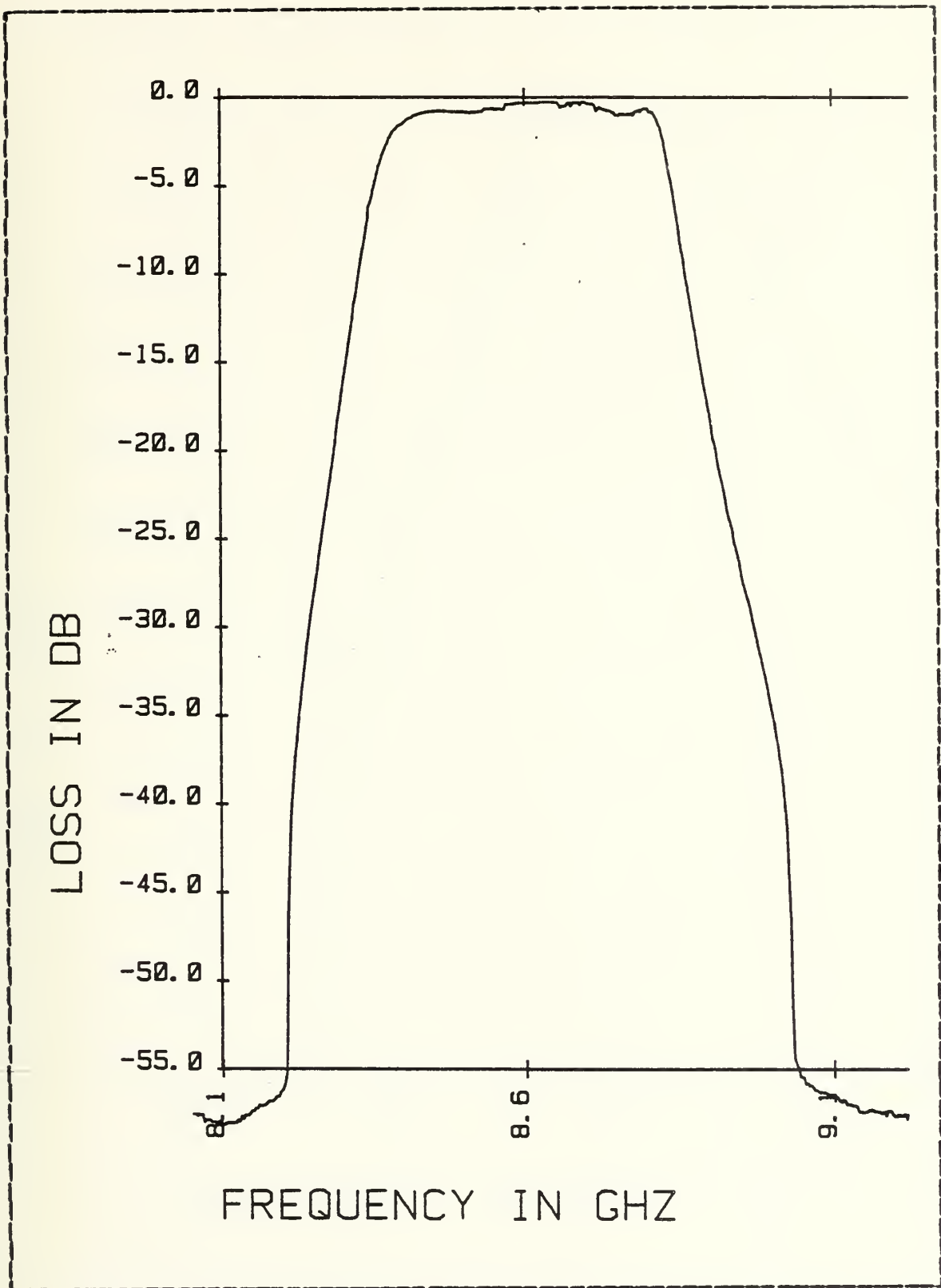


Figure 2.4 Filter Band-pass for the Third Harmonic.

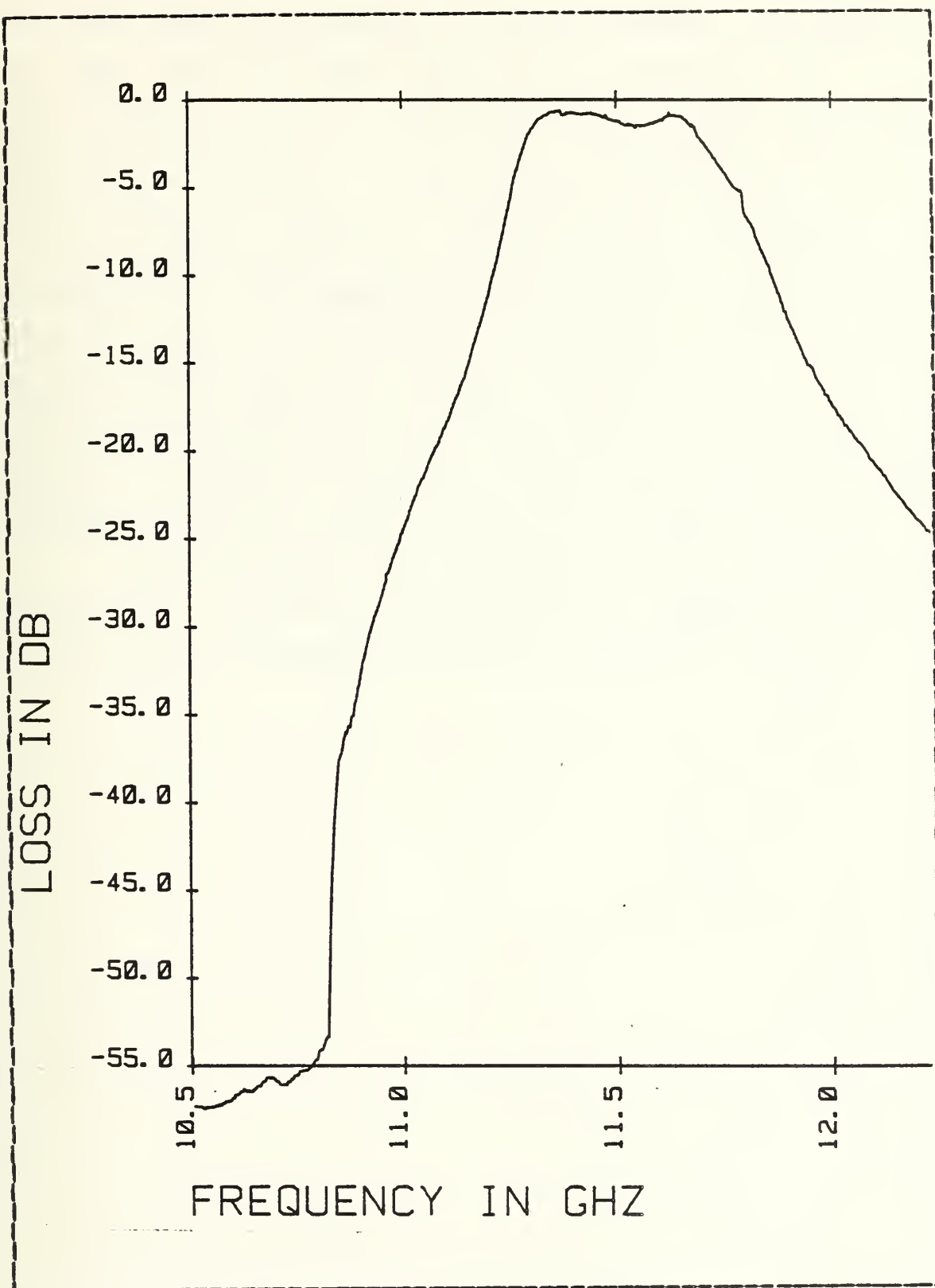


Figure 2.5 Filter Bandpass for the Fourth Harmonic.

critical piece of equipment for experimental purposes was the PHA. This instrument divided the detection range into a predetermined number of channels (e.g. 1024) and then recorded graphically the frequency with which each signal channel was detected. This allowed the observer to deal with a certain degree of variability in the signal, by choosing the observed value to be the peak of the frequency distribution. The frequency distributions observed ranged from very sharp spikes at the lower signal levels to typically broader peaks at higher signal levels. The PHA display also provided an measure of LINAC stability. If the frequency distribution of the detected signal was extremely broad or if multiple peaks were formed while detection angle remained constant, machine instabilities were indicated.

This concludes the discussion of the experimental apparatus. Comparison of experimental results to theoretical curves is presented in the next chapter.

III. RESULTS

A. METHOD OF DATA REDUCTION

As explained in Chapter 2, the raw data from the experiment was in the form of signal (power) versus angle. Since the signal was processed through a series of elements (filter, detector, amplifier, PHA), a measurement of the absolute power was not available. Therefore, it was necessary to normalize these measurements in order to make comparisons with the theoretical curves. The method of normalization chosen was the matching of peaks. For a given experiment, the experimental points were examined to determine which one had the peak value. This value was then adjusted such that it exactly matched (in magnitude) the peak value of the appropriate theoretical curve. All other experimental points for that experiment were then adjusted by the same factor, so that the experimental points maintained the same relative magnitudes.

B. DATA

The results presented here are characteristic for the experiments which were performed. Each figure shows the theoretical curve for the harmonics assumed to be present for a given filter, with the experimental points overlaid and normalized to the peak value of the theoretical curve. Tabular data for figures 3.1 through 3.5 are presented in Appendix E. Figure 3.1 and 3.2 compare the theoretical curves for harmonics three and four to the radiation measured with the appropriate filters inserted before the detector. Figure 3.3 compares the theoretical curve for the sum of harmonics three through seven with the radiation

measured with an X-band waveguide inserted before the detector.

These results appear to be good enough to indicate an initial verification of the theory. Results were best for the fourth harmonic (figure 3.2), with very close agreement between theory and experimental points. The experimental results for the third harmonic (figure 3.1) are shifted somewhat to the left of theory, while the results for the sum of harmonics (figure 3.3) are shifted to the right.

One predicted effect which is clearly evident despite the shifting is the relative spread of the Cerenkov angle for different harmonics. The third harmonic is predicted to spread the radiation over a broader range of angles than does the fourth harmonic, and this is verified by the experimental results.

There are several possible explanations for the deviations from theory which are shown here. For example, certain assumptions necessary for theoretical simplicity may not hold in the experimental situation. It may be that the charge distribution of the electron bunches is not Gaussian, or that a lateral parameter should be included in the Gaussian to account for divergence of the beam over the air path. Another factor possibly affecting the results was the mirror tilt, which caused the air path length to be longer than one meter on one side of the beam, and shorter on the other.

Another factor which must affect the results to some degree is simply the experimental geometry. For a number of reasons, theory calls for the field point distances to be much greater than the source point distances. That is, the path length should be small in relation to the distance to the point at which the fields are measured. However, the dimensions of the LINAC end station prohibit this, so that at angles larger than just a few degrees, there is ambiguity

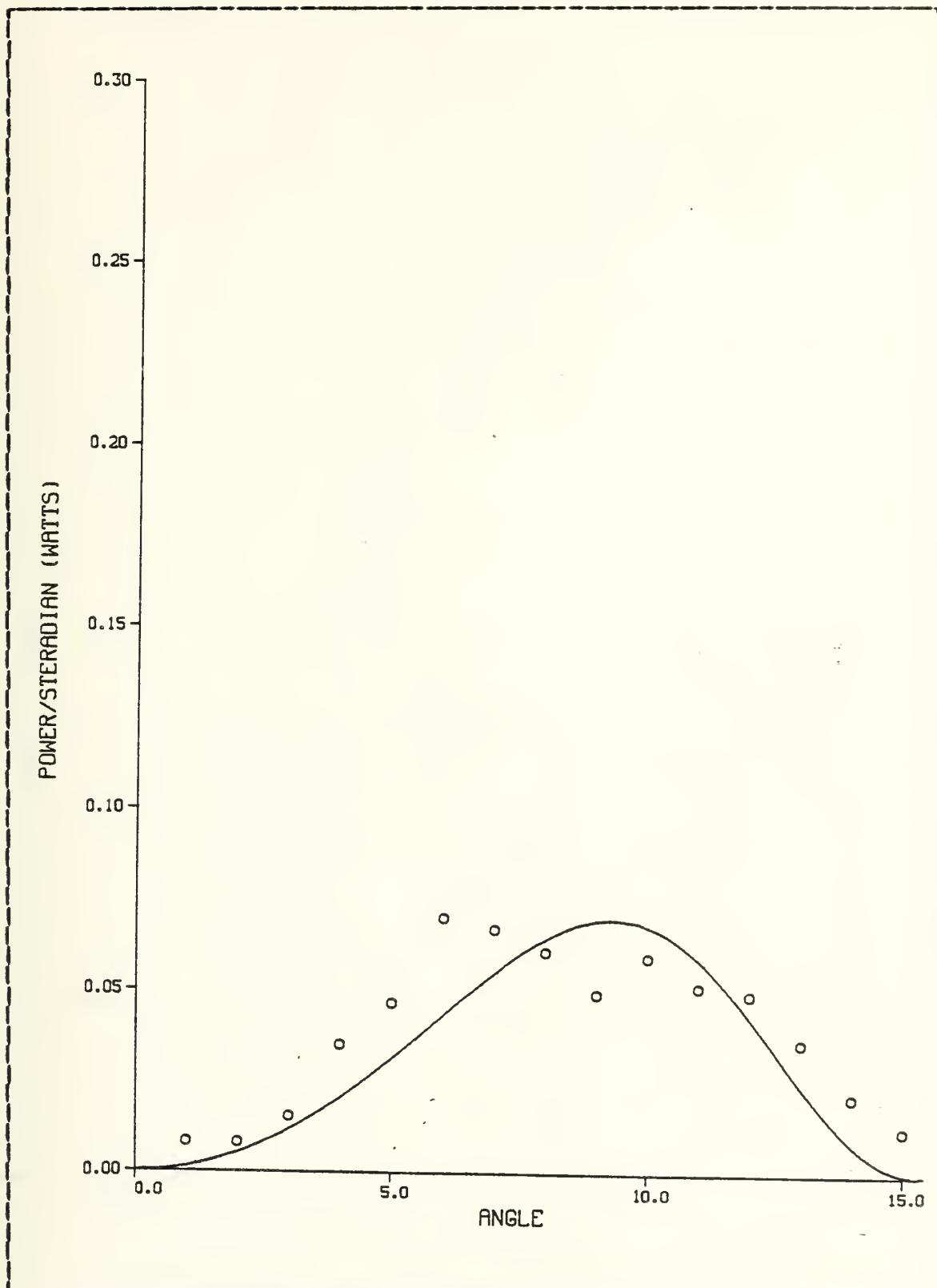


Figure 3.1 Harmonic=3 : L=1.0 m: Filter = 3rd.

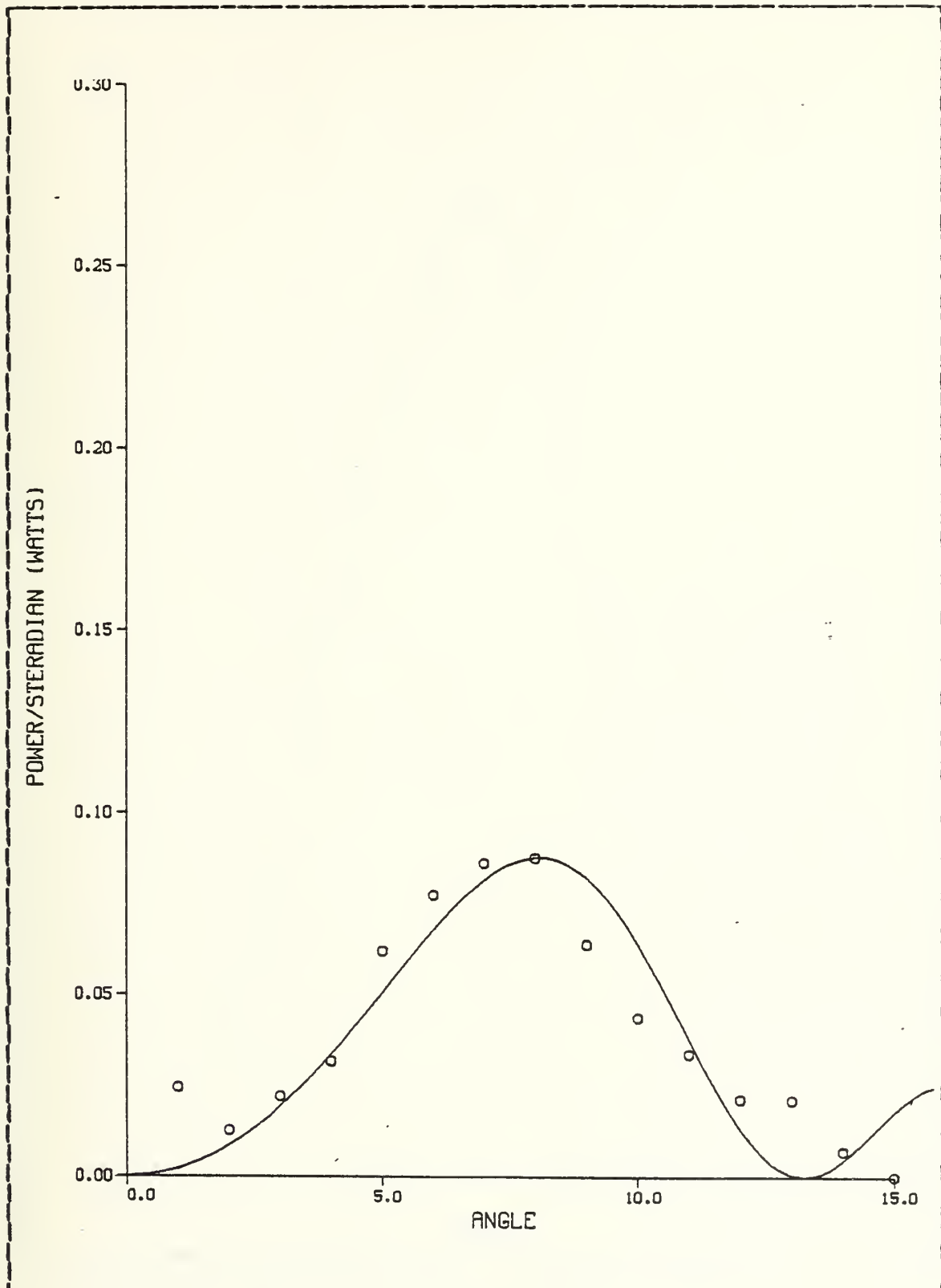


Figure 3.2 Harmonic=4 : L = 1.0 m : Filter=4th.

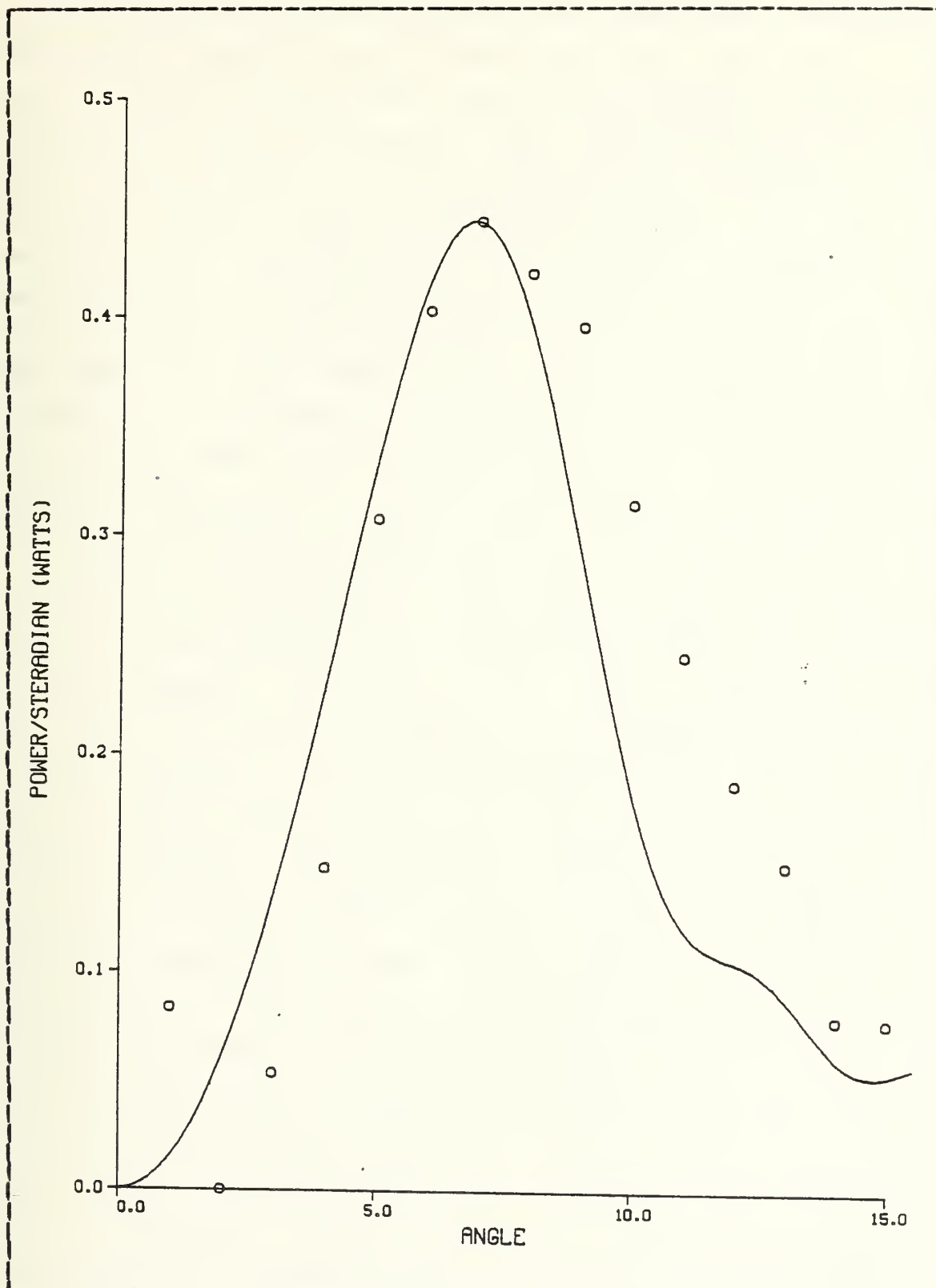


Figure 3.3 Harmonics= 3-7 : L = 1.0 m : Filter = Waveguide.

regarding exactly which angle is being measured. For small observation angles, the air path does look like a point, but as the angles become larger there are increasing differences between the angle as measured from the beginning of the air path and the angle as measured from the end of the air path. At large angles (greater than five degrees) the angle as measured from the center of the air path is substantially smaller than that measured from the end of the path. Since the radiation originating from the end of the path is stronger (it has traveled a smaller distance to the detector), and since this radiation originates at an angle larger than that which is being measured, the radiation at the measured angle is actually overstated. This may be the cause of the shift to higher angles observed in figure 3.3.

Finally, the frequency range over which the filters are valid must be considered. The X-band filters and waveguide used in this experiment are designed for use with radiation in the frequency range 8.2 to 12.4 GHz. Radiation within this band will only propagate in the dominant TE mode in X-band waveguide. Note that this encompasses only the third (8.57 GHz) and the fourth (11.42 GHz) harmonics of the LINAC bunch frequency. When radiation outside this frequency band is fed into the waveguide (as with the fifth and higher harmonics of the bunch frequency which are expected in Cerenkov radiation), modes other than the dominant may be excited in the waveguide. As indicated by [Ref. 6], the effects of coupling multiple modes into and out of a waveguide are complex, and the normal single probe configuration for detecting signal energy in the dominant mode cannot be reliably used in this situation. Since frequencies outside the X-band operating range were expected to be present in this experiment, modes higher than the dominant may have been excited, thereby causing inaccuracies in the measurement of power by the signal detector.

A comparison was made to test for the possibility that frequencies outside the X-band operating range were not being accurately measured by the single probe detector. Figure 3.3 compares the theoretical sum of harmonics 3-7 with the data measurements from the X-band waveguide, using no filter in the waveguide. Adding higher harmonics to the sum, although theoretically correct, would cause a larger discrepancy between theory and experiment, since higher harmonics are shifted towards smaller angles. Assuming the worst case, that harmonics five and above excite modes in the waveguide which are somehow not correctly coupled and detected, implies the possibility that only harmonics three and four are being measured when X-band waveguide is used as a filter. Figure 3.4, showing the data gathered with the waveguide filter normalized against the sum of harmonics three and four, appears to fit the data better, in that the width of the theoretical curve is more closely approximated by the experimental points than in figure 3.3. This lends some credence to the supposition that the detector does not respond well to harmonics higher than the fourth.

A second comparison was made to investigate the possibility that the filters which were used to isolate the third and fourth harmonics were also passing higher resonant frequencies. Such higher frequencies would be close to multiples of the frequency which the filter was designed to pass. For example, figure 3.1 compares the data gathered with the filter for the third harmonic to the theoretical curve for the third harmonic. Figure 3.5 compares the same data to the theoretical sum of the third and sixth harmonics. Note that a somewhat better fit of the data at the smaller angles is obtained in figure 3.5, indicating that the filter may be passing higher resonant frequencies, which in this case are measured by the detector, despite the effects of higher modes which may have been excited.

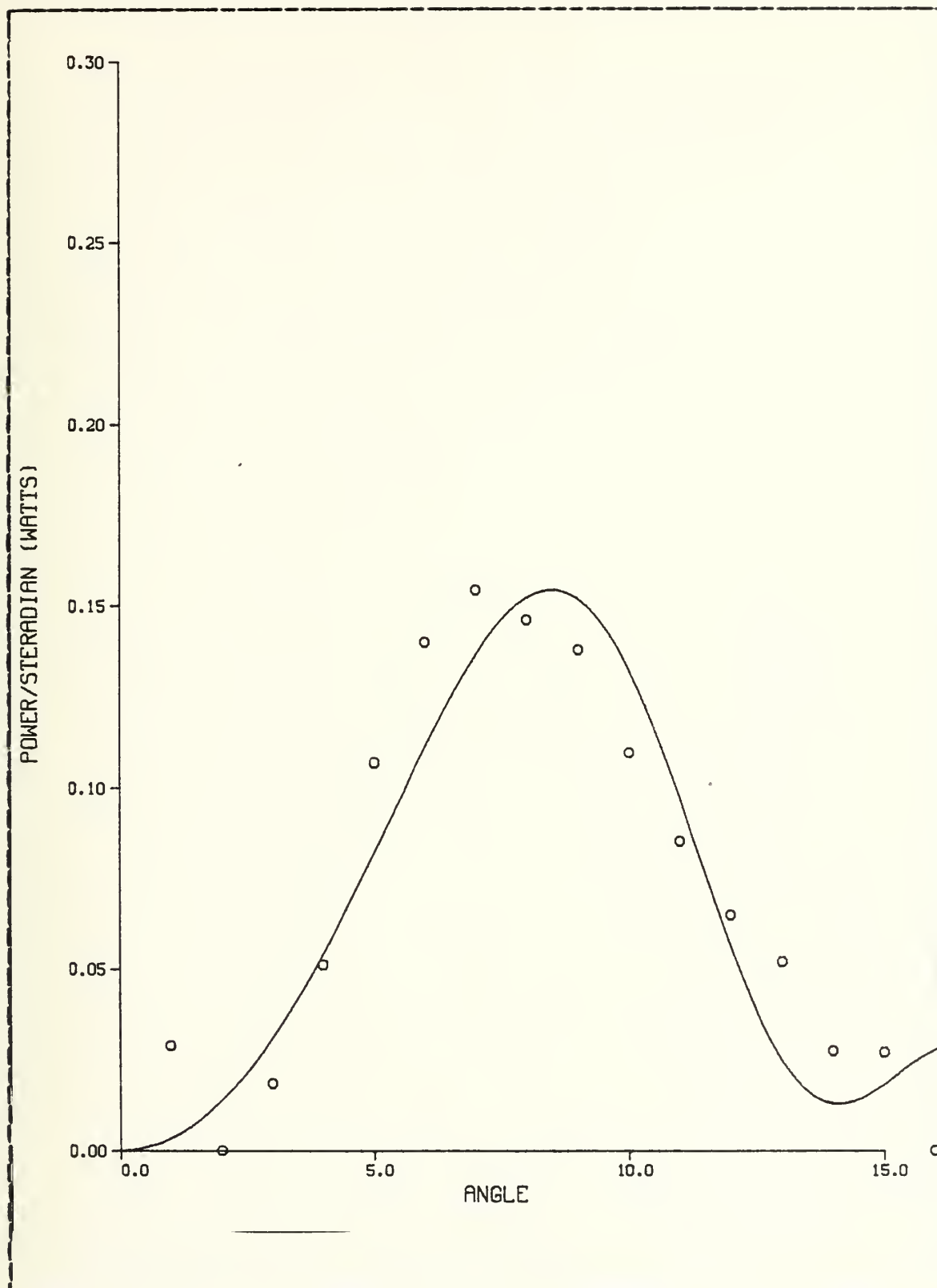


Figure 3.4 Harmonics= 3 + 4 : L=1.0 m : Filter = Waveguide.

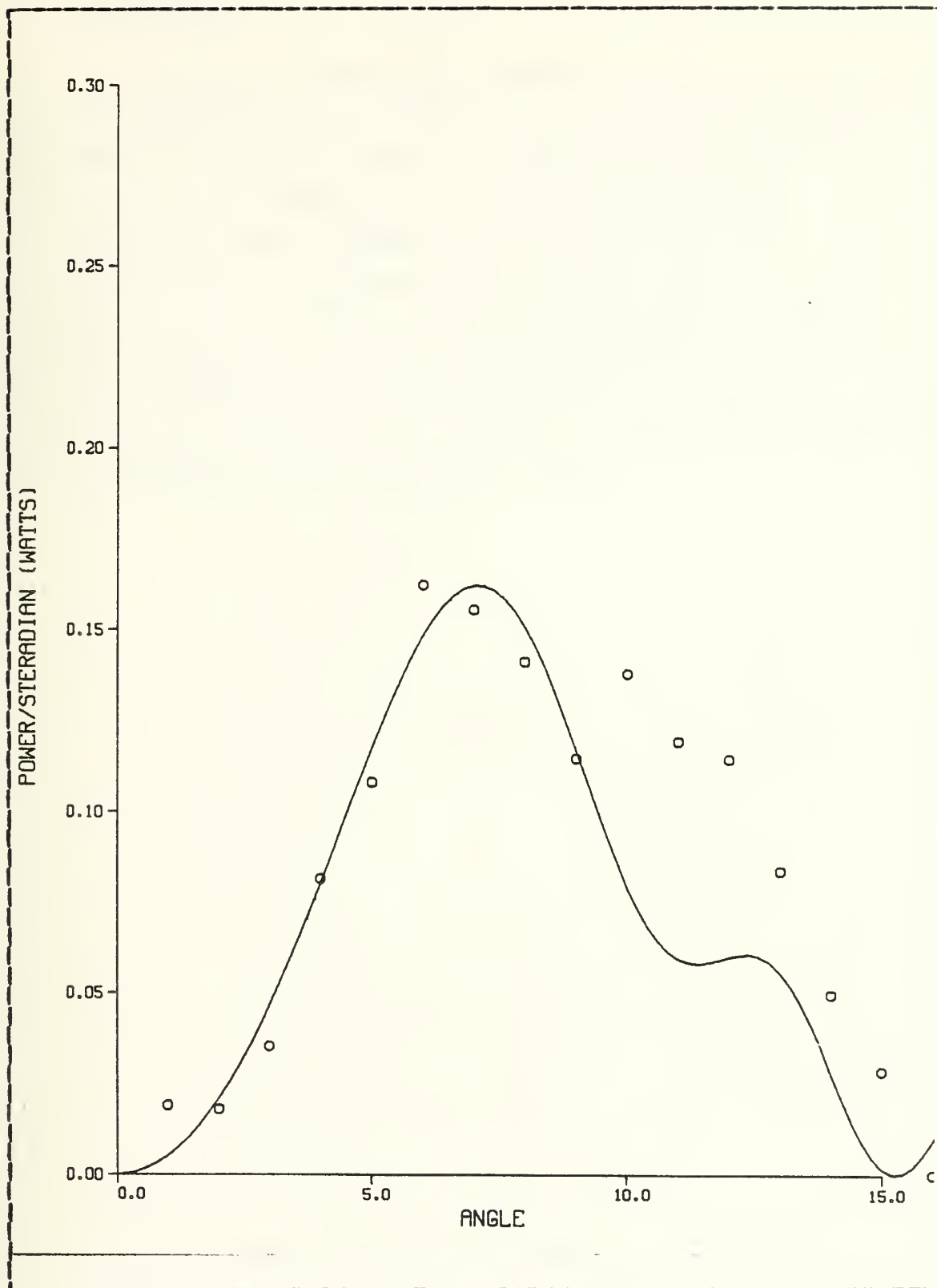


Figure 3.5 Harmonics= 3 + 6 : L=1.0 m : Filter = 3rd.

C. CONCLUSIONS

The results presented here demonstrate initial confirmation of the theory. Although it is difficult to improve the geometry of the experiment, definite improvements can be made in the measurement of the microwave radiation. Instead of using waveguide filters and a crystal detector (the use of which leads to measurement ambiguities for harmonics greater than the fourth), a tunable YIG filter coupled to a spectrum analyzer of appropriate sensitivity should be used. This will enable the observer to isolate harmonics for measurement without ambiguity, as well as allowing the measurement of absolute (vice relative) power.

APPENDIX A

FORTRAN PROGRAM FOR CALCULATING CERENKOV RADIATION CURVES

This is an interactive program which calculates and plots Cerenkov radiation curves for the case of a finite path length. Up to five different harmonics of the electron bunch frequency and five different lengths of emission path may be selected for presentation. The program also allows for adjustment of all basic parameters and constants of the Cerenkov power equation. A different curve will be plotted for each distinct combination of path length and harmonic.


```

C THIS PROGRAM CALCULATES AND PLOTS CERENKOV RADIATION CURVES. UP TO
C FIVE HARMONICS AND FIVE LENGTHS OF EMISSION REGION MAY BE CHOSEN.
C A DIFFERENT CURVE WILL BE PLOTTED FOR EACH DISTINCT COMBINATION OF
C LENGTH AND HARMONIC.
C
C REAL N, MU, KAY, MO, NUO, IF,B,C,GAMMA,BETA,V,CCSTC,
* DIMENSION W(1000), THETA(1000), HARM(5), CELL (5)
C
C INITIALIZE CONSTANTS
C DATA ICC/CO, //,IN/.N //,IMU/.MU //,INUO/.NUO //,
* IG/.Q //,IE/.E //,IMO/.MO //,IB/.B //,IY/.Y//,INO/.N//
C NPCINT = 101
C THETA1F = 20.0
C PI = 3.14159265359
C DGTICRC = 0.0174532925199
C RD1CDG = 57.29577951308
C
C *** INITIALIZE PROGRAM CONSTANTS
C CO = 2.997925E08
C N = 1.000268E00
C MU = 1.256E-06
C NUC = 2.85E09
C QE = 1.94E-12
C E = 1.6E-11
C MO = 5.10953E-31
C B = .0024E00
C
C *** ARE PROGRAM CONSTANTS OK?
C WRITE(6,90C) CO,N,MU,NUO,Q,E,MO,B
C REAL(5,901) IANS
C IF (IANS.EQ.INC) GO TO 40
C *** NO, PROGRAM CONSTANTS NEED TO BE CHANGED
C WRITE(6,902)
C REAL(5,903) IANS
C
C IF (IANS.NE.IC0) GO TO 11
C WRITE(6,904) IANS
C READ(5,*) CO
C CC TC 10
C
C IF (IANS.NE.IN) GO TO 12
C WRITE(6,904) IANS
C READ(5,*) N
C CC TC 10
C
C IF (IANS.NE.IMU) GO TO 13
C WRITE(6,904) IANS

```



```

C THE AREA IN INCHES BY INCHES:
C CALL AREA2D(7.0,10.0)
C
C WHAT EVER LABELS DESIRED ON X AND Y AXIS:
C CALL XNAME (.ANGLE$,100)
C CALL YNAME (.PCWHER/STERADIAN ( WATTS) $,100)
C CALL YA>ANG(O)
C
C WHAT EVER HEADING DESIRED FOR GRAPH:
C CALL HEADIN(.THIS IS A HEADING$,100,1.2,2)
C CALL HEADIN(.HEADING ON NEXT LINE$,100,1.2,2)
C
C RANGE AND INCREMENTS OF X AND RANGE AND INCREMENTS OF Y
C CALL GRAF (O.O, 5.0,15.0, O.O, .01,O.15)
C
C NEED SPLINE FOR SMOOTH FIT (OTHERWISE GET LINEAR FIT)
C CALL SPLINE
C DO 70 J=1,5
C IF (.HARM(J).EQ.O) GC TO 70
C
C DO 75 K = 1,5
C IF (.CELL{K}.EQ.O) GO TO 70
C
C *** BEGIN CALCULATIONS
C C=CO / N
C GAMMA = E / (MO*CO*CO)
C BETA = (1.0 - 1.0 / (GAMMA*GAMMA)) ** 0.5
C V=BETA * CO
C CCSTC=C / V
C C1=MU*C*NUC*NNUO*Q*Q / (8.0*PI*PI)
C KAY = 2.0*PI*HARM(J)*NNUO / C
C
C WRITE(50,*) KAY,COSTC,HARM(J), CELL(K)
C
C *** CALCULATE FUNCTIONAL VALUES
C RADCF=THETAF* DGTORD
C XFCINT= FLOAT(NPOINT-1)
C DO 80 I=1,NPCINT
C RATIO=FLGAT(I-1)/XPOINT
C ANGLE=RATIO*RADF
C THETA(I)=RATIO*THE TAF
C F=1/(EXP (O.25 * B*KAY*CCS(ANGLE) * B*KAY*CCS(ANGLE)))
C U=(KAY * CELL(K) * (CCSTC-CCS(ANGLE)))/2
C IF (= SIN(U) / U
C W(I) = (F*KAY*CELL(K))*SIN(ANGLE)*IF)**2

```



```

C 80      WRITE(50,*) W(I),THETA(I),F,IF
C          CONTINUE
C      CALL CURVE FOR EACH CURVE DESIRED (O IN LAST PARAMETER
C      INDICATES CO NOT DISPLAY DATA POINTS, 1 MEANS DISPLAY
C      EVERY DATA PCINT)
C      CALL CLFVE (THETA,W,NPOINT,O)
C      CALL CLFVE (X,Y,N,O)
C      CALL CLFVE (X,YY,N,O)
C 75      CONTINUE
C 70      CONTINUE
C          CALL ENDPL(O)
C      ** USER WANT ANOTHER RUN?
C          WRITE(6,508)
C          REAL(5,901) IANS
C          IF(IANS.EQ.1Y) GO TO 10
C 90      CALL DCNEPL
C          CONTINUE
C          STOP
C 900      FORMAT(/,' PROGRAM CONSTANTS CURRENTLY HAVE VALUES AS FOLLOWS:','/
*      ,5X,'CC = SPEED OF LIGHT IN VACUUM = ,E14.7, //
*      ,5X,'N = AIR REFRACTIVE INDEX = ,E14.7, //
*      ,5X,'ML = PERMEABILITY CF AIR = ,E14.7, //
*      ,5X,'NLO = BUNCH FREQUENCY = ,E14.7, //
*      ,5X,'C = ELECTRON CHARGE = ,E14.7, //
*      ,5X,'E = ELECTRON ENERGY = ,E14.7, //
*      ,5X,'MC = ELECTRON REST MASS = ,E14.7, //
*      ,5X,'B = BUNCH SIZE PARAMETER = ,E14.7, //
*      ,5X,'YCU WANT TO CHANGE ANY OF THESE VALUES? ( Y OR N )')
C          FORMAT(A1)
C          FORMAT(/,' ENTER CCNSTANT TO BE CHANGED:')
C          FORMAT(A4)
C          FORMAT(' ENTER NEW VALUE FOR ',A4,':')
C          FORMAT(' ENTER VALUES FOR HARM (HARMONIC OF BUNCH FREQUENCY):')
C          FORMAT(' ENTER VALUES FOR CELL (LENGTH CF EMISSION REGION):')
C          FORMAT(' ENTER ANOTHER RUN? ( ENTER Y OR N )')
C          FORMAT(' WANT ANOTHER RUN? ( ENTER Y OR N )')
C          FORMAT(' THE VARIABLE SELECTED IS NOT IN THE LIST - TRY AGAIN')
C          END
CER01450
CER01460
CER01470
CER01480
CER01490
CER01500
CER01510
CER01520
CER01530
CER01540
CER01550
CER01560
CER01570
CER01580
CER01590
CER01600
CER01610
CER01620
CER01630
CER01640
CER01650
CER01660
CER01670
CER01680
CER01690
CER01700
CER01710
CER01720
CER01730
CER01740
CER01750
CER01760
CER01770
CER01780
CER01790
CER01800
CER01810
CER01820
CER01830
CER01840
CER01850
CER01860
CER01870
CER01880
CER01890
CER01900

```


APPENDIX B

FORTTRAN PROGRAM - CERENKOV CURVES WITH DATA POINTS

This is an interactive program which calculates and plots several Cerenkov radiation curves as well as a single set of experimentally observed data points. Up to five different harmonics of the bunch frequency and five different lengths of the emission path may be chosen for presentation. A different curve will be plotted for each distinct combination of path length and harmonic. The program also allows adjustment of all basic parameters and constants of the Cerenkov power equation. The program then prompts for 20 data measurements of power (one per degree) which will be superimposed over the curves.


```

C THIS PROGRAM CALCULATES AND PLOTS CERENKOV RADIATION CURVES FOR
C UP TO FIVE DIFFERENT HARMONICS AND FIVE DIFFERENT LENGTHS OF
C EMISSION REGION. A DIFFERENT CURVE WILL BE CALCULATED FOR EACH
C DISTINCT COMBINATION OF LENGTH AND HARMONIC. THE PROGRAM THEN ASKS
C FOR 20 DATA PCINTS (ONE PER DEGREE) TC BE SUPERIMPOSED OVER THE
C CURVES.
C
C REAL N, MU, KAY, MO, NUO, IF, B, C, GAMMA, BETA, V, COSTC,
C * DIMENSION W(1000), THETA(1000), HARM(5), CELL (5), THE TAP(20),
C * PCWER(20),
C
C INITIALIZE CONSTANTS
C DATA ICC/CO, /,IN/ N, /,IMU/ MO, /,INUC/ NUO, /,
C * IC/ Q, /,IE/ E, /,IMO/ MO, /,IB/ E, /,IY/ Y, /,INO/ N, /
C * NPCINT = 101
C THETAF = 20.0
C PI = 3.14159265359
C DGTICRD = 0.0174532925199
C RDTICDG = 57.29577551308
C
C *** INITIALIZE PROGRAM CONSTANTS
C CO = 2.997925E08
C N = 1.000268E00
C MU = 1.254E-06
C NUO = 2.85E09
C Q = 1.94E-12
C E = 1.6E-11
C MO = 9.10953E-31
C B = .0024E00
C
C ARE PROGRAM CONSTANTS OK?
C WRITE(6,900) CO,N,MU,NUO,Q,E,MO,B
C
C READ(5,901) IANS
C IF (IANS.EQ.INC) GC TO 40
C NO PROGRAM CONSTANTS NEED TO BE CHANGED
C WRITE(6,902)
C REAL(5,903) IANS
C
C IF (IANS.NE.IC0) GO TO 11
C WRITE(6,904) IANS
C READ(5,*) CO
C GC TC 10
C
C IF (IANS.NE.IN) GO TO 12
C WRITE(6,904) IANS
C READ(5,*) N
C GC TC 10
C
C CER000G10
C CER000C20
C CER000C30
C CER000C40
C CER000C50
C CER000060
C CER000C70
C CER000C80
C CER000090
C CER000C100
C CER000C110
C CER000C120
C CER000C130
C CER000C140
C CER000C150
C CER000C160
C CER000C170
C CER000C180
C CER000C190
C CER000C200
C CER000C210
C CER000C220
C CER000C230
C CER000C240
C CER000C250
C CER000C260
C CER000C270
C CER000C280
C CER000C290
C CER000C300
C CER000C310
C CER000C320
C CER000C330
C CER000C340
C CER000C350
C CER000C360
C CER000C370
C CER000C380
C CER000C390
C CER000C400
C CER000C410
C CER000C420
C CER000C430
C CER000C440
C CER000C450
C CER000C460
C CER000C470
C CER000C480

```


CEROC490
CEROC500
CEROC510
CEROC520
CEROC530
CEROC540
CEROC550
CEROC560
CEROC570
CEROC580
CEROC590
CEROC600
CEROC610
CEROC620
CEROC630
CEROC640
CEROC650
CEROC660
CEROC670
CEROC680
CEROC690
CEROC700
CEROC710
CEROC720
CEROC730
CEROC740
CEROC750
CEROC760
CEROC770
CEROC780
CEROC790
CEROC800
CEROC810
CEROC820
CEROC830
CEROC840
CEROC850
CEROC860
CEROC870
CEROC880
CEROC890
CEROC900
CEROC910
CEROC920
CEROC930
CEROC940
CEROC950
CEROC960

```

C 12      IF(IANS.NE.IMU) GO TO 13
           WRITE(6,904) IANS
           READ(5,*) MU
           GC TC 10

C 13      IF(IANS.NE.INUO) GO TO 14
           WRITE(6,904) IANS
           READ(5,*) NUO
           GC TC 10

C 14      IF(IANS.NE.IQ) GO TO 15
           WRITE(6,904) IANS
           READ(5,*) Q
           GC TC 10

C 15      IF(IANS.NE.IE) GO TO 16
           WRITE(6,904) IANS
           READ(5,*) E
           GC TC 10

C 16      IF(IANS.NE.IMO) GO TO 17
           WRITE(6,904) IANS
           READ(5,*) MO
           GC TC 10

C 17      IF(IANS.NE.IB) GO TO 18
           WRITE(6,904) IANS
           READ(5,*) B
           GC TC 10

C 18      *** ERROR
           WRITE(6,910)
           GC TO 10

C 40      WRITE(6,905)
           READ(5,*) HARM(1), HARM(2), HARM(3), HARM(4), HARM(5)
           WRITE(6,906)
           READ(5,*) CELL(1), CELL(2), CELL(3), CELL(4), CELL(5)

C          WRITE(6,907)
           DO 41 I = 1,20
             READ(5,*) POWER(I)
           CONTINUE

C          DO 42 I = 1,20
             TAP(I) = I
           CONTINUE

```



```

C *** CALCULATE FUNCTIONAL VALUES
C RACF = THETAF * DGTORD
C XPOINT = FLOAT(NPCINT-1)
C DC 80 I=1,NPCINT
C   RATIO = FLPCAT(I-1) / XPOINT
C   ANGLE = RATIO * RADF
C   THETA(I) = RATIO * THETAF
C   F = 1/(EXP(0.25 * B*KAY*CCOS(ANGLE) * B*KAY*CCOS(ANGLE)))/2
C   U = (KAY * CELL(K) * (COSTC-COS(ANGLE)))/2
C   IF = SIN(U) / U
C   W(I) = CI * (F*KAY*CELL(K)*SIN(ANGLE)*IF)**2
C   WRITE(50,*) W(I),THETA(I),F,IF
C   CONTINUE
C 80 CALL CURVE FOR EACH CURVE DESIRED (0 IN LAST PARAMETER
C INDICATES CG NOT DISPLAY DATA POINTS, 1 MEANS DISPLAY
C EVERY DATA POINT)
C   CALL CURVE (THETA,W,NPOINT,0)
C   CALL CLFVE (X,Y,N,0)
C   CALL CLFVE (X,Y,N,0)
C 75 CONTINUE
C 70 CONTINUE
C   CALL CURVE (THETAP,POWER,20,-1)
C   CALL ENCP(LC)
C ** USER WANT ANOTHER RUN?
C   WRITE(6,508)
C   REAC(5,901) IANS
C   IF(IANS.EQ.IY) GC TC 10
C   CALL DCNEPL
C   CONTINUE
C   STOP
C 90
C 900 FORMAT(/,' PROGRAM CONSTANTS CURRENTLY HAVE VALUES AS FOLLOWS: ',/
C ,5X,'CC = SPEED OF LIGHT IN VACUUM =',E14.7,/,/
C ,5X,'N = AIR REFRACTIVE INDEX =',E14.7,/,/
C ,5X,'ML = PERMEABILITY CF AIR =',E14.7,/,/
C ,5X,'NLO = BUNCH FREQUENCY =',E14.7,/,/
C ,5X,'C = ELECTRON CHARGE =',E14.7,/,/
C ,5X,'E = ELECTRON REST MASS =',E14.7,/,/
C ,5X,'PC

```


APPENDIX C

FORTRAN PROGRAM - SUM OF CERENKOV CURVES WITH DATA POINTS

This is an interactive program which calculates and plots a single Cerenkov radiation curve and superimposes a single set of data points over the curve. The single Cerenkov curve will represent a sum of curves. The sum will be composed of each distinct combination of harmonic and path length chosen. Up to five different lengths of emission path and five different harmonics of the bunch frequency may be chosen. The program also allows adjustment of all basic parameters and constants of the Cerenkov power equation. The program will prompt for 20 data measurements of power (one for each degree of angle).

SUM0C490
SUM0C500
SUM0C510
SUM0C520
SUM0C530
SUM0C540
SUM0C550
SUM0C560
SUM0C570
SUM0C580
SUM0C590
SUM0C600
SUM0C610
SUM0C620
SUM0C630
SUM0C640
SUM0C650
SUM0C660
SUM0C670
SUM0C680
SUM0C690
SUM0C700
SUM0C710
SUM0C720
SUM0C730
SUM0C740
SUM0C750
SUM0C760
SUM0C770
SUM0C780
SUM0C790
SUM0C800
SUM0C810
SUM0C820
SUM0C830
SUM0C840
SUM0C850
SUM0C860
SUM0C870
SUM0C880
SUM0C890
SUM0C900
SUM0C910
SUM0C920
SUM0C930
SUM0C940
SUM0C950
SUM0C960

```

C 12      IF(IANS.NE.IMU) GO TO 13
           WRITE(6,904) IANS
           READ(5,*) MU
           GO TO 10

C 13      IF(IANS.NE.INUC) GO TO 14
           WRITE(6,904) IANS
           READ(5,*) NUO
           GO TO 10

C 14      IF(IANS.NE.IQ) GO TO 15
           WRITE(6,904) IANS
           READ(5,*) C
           GO TO 10

C 15      IF(IANS.NE.IE) GO TO 16
           WRITE(6,904) IANS
           READ(5,*) E
           GO TO 10

C 16      IF(IANS.NE.IMO) GO TO 17
           WRITE(6,904) IANS
           READ(5,*) MO
           GO TO 10

C 17      IF(IANS.NE.IB) GO TO 18
           WRITE(6,904) IANS
           READ(5,*) B
           GO TO 10

C 18      ** ERROR
           WRITE(6,910)
           GO TO 10

C 40      WRITE(6,905)
           READ(5,*) HARM(1), HARM(2), HARM(3), HARM(4), HARM(5)
           WRITE(6,906)
           READ(5,*) CELL(1), CELL(2), CELL(3), CELL(4), CELL(5)

C          WRITE(6,907)
           DO 41 I=1,20
           READ(5,*) POWER(I)
           CONTINUE

C 41      DO 42 I=1,20
           TETAP(I) = I
           CONTINUE

C 42

```



```

C      C1 = MU*C*NUO*NUO*Q*G / (8.0*PI*PI)
C      KAY = 2.0*PI*HARM(J)*NUO / C
C      WRITE(50,*) KAY,COSTC,HARM(J), CELL(K)
C
C      *** CALCULATE FUNCTIONAL VALUES
C      RADF = THETA*F * DGTORD
C      XFCINT = FLOAT(NPOINT-1)
C      CC 80 I=1,NPCINT
C          RATIO = FLOAT(I-1) / XPOINT
C          ANGLE = RATIO * RADF
C          THETA(I) = RATIO * THETA*F
C          F = 1/(EXP(0.25 * B*KAY*CCOS(ANGLE) * B*KAY*CCOS(ANGLE)))/2
C          U = (KAY * CELL(K) * (COSTC-COS(ANGLE)))/2
C          IF = SIN(U) / (F*KAY*CELL(K)*SIN(ANGLE)*IF)**2
C          W(I) = C1 * (F*KAY*CELL(K)*SIN(ANGLE)*IF)**2
C          SUM(I) = W(I) + SUM(I)
C          WRITE(50,*) SUM(I),THETA(I)
C          WRITE(50,*) W(I),THETA(I),F,IF
C      CONTINUE
C
C      CALL CURVE FOR EACH CURVE DESIRED (0 IN LAST PARAMETER
C      INDICATES CC NOT DISPLAY DATA POINTS, 1 MEANS DISPLAY
C      EVERY DATA POINT)
C      CALL CURVE (THETA,W,NPOINT,0)
C      CALL CURVE (X,Y,N,0)
C      CALL CURVE (X,YY,N,0)
C
C      CONTINUE
C
C      CONTINUE
C
C      CALL CURVE (THETA,SUM,NPOINT,0)
C      CALL CURVE (THETAPOWER,20,-1)
C
C      CALL ENCL(0)
C
C      ** USER WANT ANOTHER RUN?
C      WRITE(6,508)
C      REAC(5,901) IANS
C      IF (IANS.EQ.1Y) GO TO 10
C      CALL DCNEPL
C      CONTINUE
C      STCP
C
C      900 FORMAT(/, ' PROGRAM CONSTANTS CURRENTLY HAVE VALUES AS FOLLOWS: ',//
SUM01450
SUM01460
SUM01470
SUM01480
SUM01490
SUM01500
SUM01510
SUM01520
SUM01530
SUM01540
SUM01550
SUM01560
SUM01570
SUM01580
SUM01590
SUM01600
SUM01610
SUM01620
SUM01630
SUM01640
SUM01650
SUM01660
SUM01670
SUM01680
SUM01690
SUM01700
SUM01710
SUM01720
SUM01730
SUM01740
SUM01750
SUM01760
SUM01770
SUM01780
SUM01790
SUM01800
SUM01810
SUM01820
SUM01830
SUM01840
SUM01850
SUM01860
SUM01870
SUM01880
SUM01890
SUM01900
SUM01910
SUM01920

```


[illegible]

APPENDIX D

EXPERIMENTAL APPARATUS

This appendix contains photographs of the experimental apparatus used in this experiment. Figure D.1 shows the end station of the LINAC. At the right is the LINAC beam aperture, with the reflecting aluminum mirror at the left. The detector assembly, mounted at the end of the pivot arm, is shown in the foreground of the photograph. Also shown, located along the beam path between the aperture and the mirror, is a small portable laser used to align the mirror.

Figure D.2 shows the waveguide filter with the fin-line insert for one of the harmonics, along with the detector and horn. Figure D.3 shows the detector apparatus assembled.

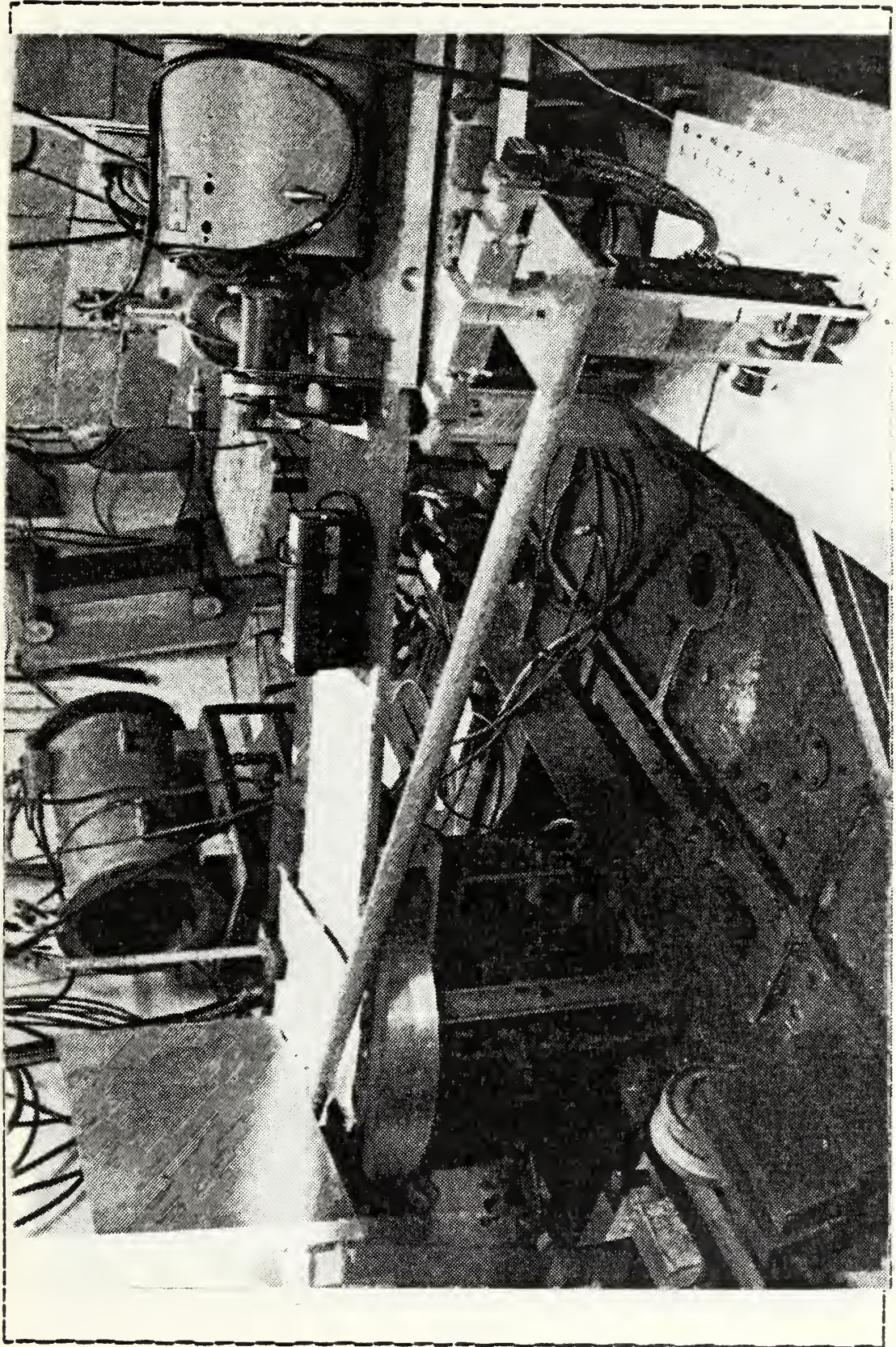


Figure D.1 LINAC End-Station.

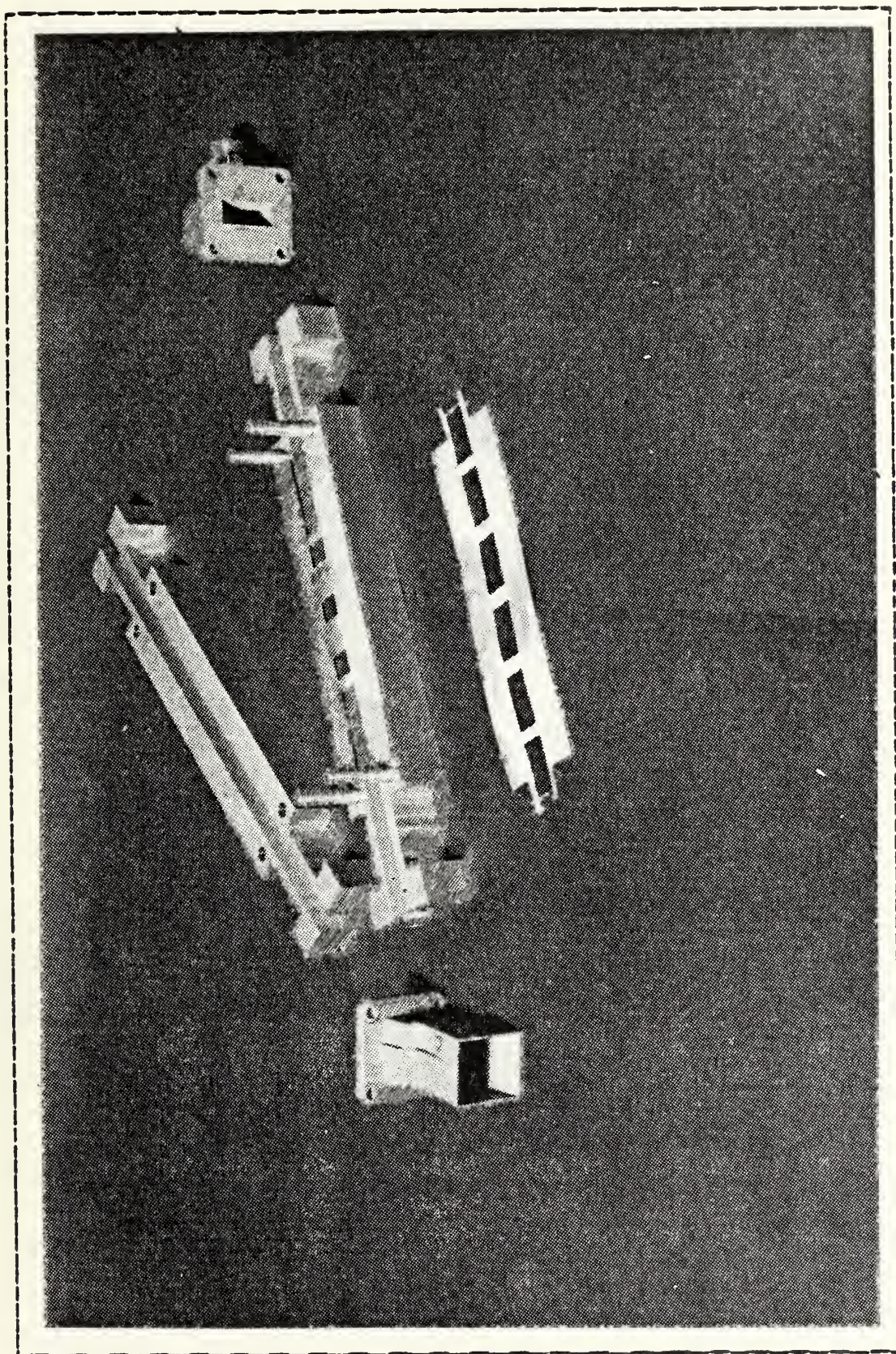


Figure D.2 Detection Apparatus Components.

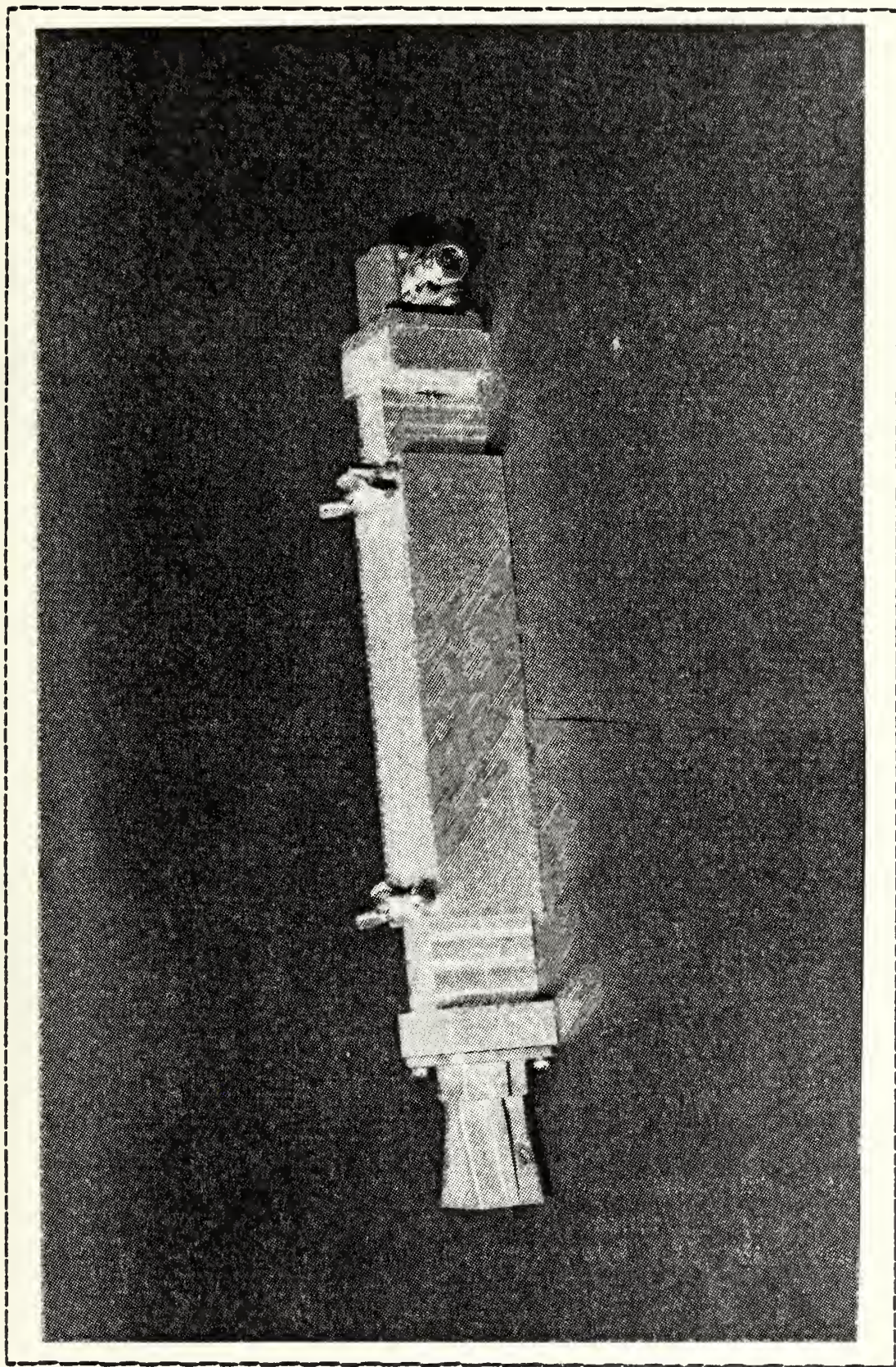


Figure D.3 Assembled Detection Apparatus.

APPENDIX E
TABULAR DATA FOR FIGURES

TABLE III
Tabular Data for Figure 3.1

Degree	Channel	Normalized Value
1	101	.0082
2	96	.0078
3	188	.0153
4	434	.0352
5	575	.0467
6	864	.0701
7	828	.0672
8	752	.0610
9	610	.0495
10	734	.0596
11	635	.0515
12	609	.0494
13	446	.0362
14	265	.0215
15	152	.0123

- Channel values were read from the Pulse Height Analyzer
- Normalizing factor was $8.1134\text{E-}05$
- Beam current = $4.0\text{E-}08$ Amps

TABLE IV
Tabular Data for Figure 3.2

Degree	Channel	⁰ Normalized Value
1	219	.0244
2	114	.0127
3	198	.0221
4	284	.0317
5	556	.0620
6	694	.0774
7	772	.0861
8	786	.0877
9	572	.0638
10	393	.0438
11	304	.0339
12	193	.0215
13	190	.0212
14	64	.0071
15	0	.0000

-Channel values were read from Pulse Height Analyzer

-Normalizing factor was 1.1158E-04

-Beam current = 4.0E-08 Amps

TABLE V
Tabular Data for Figure 3.3

Degree	Channel	Normalized Value
1	117	.0837
2	0	.0000
3	75	.0537
4	207	.1481
5	431	.3083
6	565	.4042
7	623	.4457
8	590	.4221
9	556	.3978
10	442	.3162
11	344	.2461
12	262	.1874
13	210	.1502
14	111	.0794
15	109	.0780

-Channel values were read from Pulse Height Analyzer

-Normalizing Factor was 3.9502E-04

-Beam current = 4.0E-08 Amps

TABLE VI
Tabular Data for Figure 3.4

Degree	Channel	Normalized Value
1	117	.0290
2	0	.0000
3	75	.0186
4	207	.0513
5	431	.1069
6	565	.1401
7	623	.1545
8	590	.1463
9	556	.1379
10	442	.1096
11	344	.0853
12	262	.0650
13	210	.0521
14	111	.0275
15	109	.0270

-Channel Values were read from the Pulse Height Analyzer

-Normalizing factor was $2.48\text{E}-04$

-Beam current = $4.0\text{E}-08$ Amps

TABLE VII
Tabular Data for Figure 3.5

Degree	Channel	Normalized Value
1	101	.0190
2	96	.0180
3	188	.0353
4	434	.0815
5	575	.1080
6	864	.1623
7	828	.1555
8	752	.1413
9	610	.1146
10	734	.1379
11	635	.1193
12	609	.1144
13	446	.0838
14	265	.0498
15	152	.0286

-Channel values were read from the Pulse Height Analyzer

-Normalizing factor was 1.878E-04

-Beam current = 4.0E-08 Amps

LIST OF REFERENCES

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